

No Stripped Hydrogen in the Nebular Spectra of Nearby Type Ia Supernova 2011fe¹

Benjamin J. Shappee^{2,3}, K. Z. Stanek^{2,4}, R. W. Pogge^{2,4}, and P. M. Garnavich⁵,

shappee@astronomy.ohio-state.edu, kstanek@astronomy.ohio-state.edu,
pogge@astronomy.ohio-state.edu, pgarnavi@nd.edu

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ABSTRACT

A generic prediction of the single-degenerate model for Type Ia supernovae (SNe Ia) is that a significant amount of material will be stripped from the donor star ($\sim 0.5 M_{\odot}$ for a giant donor and $\sim 0.15 M_{\odot}$ for a main sequence donor) by the supernova ejecta. This material, excited by gamma-rays from radioactive decay, would then produce relatively narrow ($\lesssim 1000 \text{ km s}^{-1}$) emission features observable once the supernova enters the nebular phase. Such emission has never been detected, which already provides strong constraints on Type Ia progenitor models. In this Letter we report the deepest limit yet on the presence of $H\alpha$ emission originating from the stripped hydrogen in the nebular spectrum of a Type Ia supernova obtained using a high signal-to-noise spectrum of the nearby normal SN Ia 2011fe 274 days after B -band maximum light with the Large Binocular Telescope’s Multi-Object Double Spectrograph. We put a conservative upper limit on the $H\alpha$ flux of $3.14 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, which corresponds to a luminosity of $1.57 \times 10^{35} \text{ erg s}^{-1}$. Assuming the models of Mattila et al. (2005) and the methods of Leonard (2007), this translates into an upper limit of $\lesssim 0.001 M_{\odot}$ of stripped material, which is an order of magnitude stronger than previous limits by Leonard (2007). SN 2011fe was a typical Type Ia supernova, special only in its proximity, and we argue that lack of hydrogen emission in its nebular spectrum adds yet another strong constraint on the single degenerate class of models for SNe Ia.

Subject headings: supernovae: Type Ia — supernovae: individual (SN 2011fe) — white dwarfs

²Department of Astronomy, The Ohio State University, Columbus, Ohio 43210, USA

³NSF Graduate Fellow

⁴Center for Cosmology & AstroParticle Physics, The Ohio State University, Columbus, OH 43210, USA

⁵Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA

¹Based on data acquired using the Large Binocular Telescope (LBT/MODS).

1. Introduction

Despite the fact that SNe Ia were used to discover the accelerating universe (Riess et al. 1998; Perlmutter et al. 1999), the physical nature of their progenitor systems remains theoretically ambiguous and observationally elusive (for a review see Wang & Han 2012). It is commonly accepted that SNe Ia result from the thermonuclear explosion of a carbon-oxygen white dwarf (WD) in a close binary system, but the nature of the binary companion and the sequence of events leading to the SN explosion are still uncertain. There are two dominant models: the double degenerate (DD) scenario, in which the companion is also a WD (Iben & Tutukov 1984; Webbink 1984), and the single degenerate (SD) scenario, in which the companion is a non-degenerate object such as a main sequence (MS) star, a red giant (RG), a sub-giant or a He star (Whelan & Iben 1973; Nomoto 1982). There are additional minor variations on these basic models of the progenitor system for both the SD channel (e.g. Justham 2011; Wheeler 2012) and the DD channel (e.g. Thompson 2011; Shappee & Thompson 2012). These uncertainties about the progenitor systems for SNe Ia remain a substantial problem for understanding the systematic errors in using SNe Ia to study cosmology (e.g. Wood-Vasey et al. 2007).

One of the observational signatures of the SD model is that the material from the companion should be stripped when struck by the SN ejecta (Wheeler et al. 1975), leading to both immediate signatures from the impact of the SN ejecta on the companion (e.g. Marietta et al. 2000; Meng et al. 2007; Pakmor et al. 2008; Pan et al. 2012b; Liu et al. 2012) and major changes in the companion’s future evolution (Podsiadlowski 2003; Shappee et al. 2012; Pan et al. 2012a). Recently, the hydrodynamic simulations of Pan et al. (2012b) and Liu et al. (2012) have shown that $\sim 0.1 - 0.2 M_{\odot}$ of solar-metallicity material is expected to be removed from MS companions by the impact of the SN ejecta. These hydrodynamic simulations show that this material will be embedded in low-velocity supernova debris with a characteristic velocity of $\lesssim 1000 \text{ km s}^{-1}$. However, the line profiles from the stripped material are somewhat uncertain because this material will be asymmetrically stripped (Liu et al. 2012), and the orientation of the binary relative to our line of sight, at the time of explosion, is unknown. This material will be hidden in early-time spectra by higher velocity, optically thick, iron-rich ejecta, but will then appear in late-time, nebular phase spectra ($\gtrsim 250$ days; Mattila et al. 2005) as the higher velocity ejecta become optically thin.

Only a handful of nebular phase, high signal-to-noise (S/N) SNe Ia spectra have been published in the literature, with the strongest limits on late-time hydrogen flux coming from Mattila et al. (2005) and Leonard (2007). Mattila et al. (2005) obtained late-time low-resolution spectra of SN 2001el, modeled the emission from solar-metallicity material stripped from a non-degenerate companion, and used both to place an upper limit of $\lesssim 0.03 M_{\odot}$ on the presence of this material. Leonard (2007) obtained deep, medium-resolution, nebular-phase, multi-epoch spectra of SN 2005am and SN 2005cf at distances ~ 37 Mpc and ~ 32 Mpc, respectively. Using the approach of Mattila et al. (2005), he placed a $\lesssim 0.01 M_{\odot}$ upper limit on the presence of any low velocity solar-abundance material in both SN. These observations seem to firmly rule out main sequence companions for these three SNe.

However, a more exotic scenario which might evade these constraints has since been proposed by Justham (2011). In this model a WD is spun up by the mass it accretes from its non-degenerate companion,

allowing the WD to remain stable above the Chandrasekhar mass and giving the companion time to evolve and contract before the SN explosion. This leaves a smaller and more tightly bound companion at the time of explosion, reducing the amount of stripped material. It therefore is of significant interest to put even stronger constraints on the amount of stripped material for other SNe Ia.

At a mere 6.4 Mpc (Shappee & Stanek 2011) the “plain vanilla” Type Ia SN (as described by Wheeler 2012) is an ideal target for obtaining improved constraints. SN 2011fe was discovered less than one day after explosion by the Palomar Transient Factory (Law et al. 2009) in the Pinwheel Galaxy (M101), a well-studied, nearby face-on spiral. This SN is the nearest Ia in the last 25 years and the early detection and announcement allowed extensive multi-wavelength follow-up observations. Additionally, SN 2011fe is only slightly reddened and is surrounded by a relatively “clean” environment (Patat et al. 2011). Brown et al. (2012) and Bloom et al. (2012) used the very early-time UV and optical observations to constrain the shock heating that would occur as the SN ejecta collide with the companion, ruling out giants and main sequence secondaries more massive than the Sun. These constraints appear to rule out SD models; however, these studies both rely on Kasen (2010), which assumes a Roche-lobe overflowing secondary with a typical stellar structure and depends on the orientation of the binary relative to our line of sight. However, Meng et al. (2007) pointed out that the secondary will be left smaller and more compact than a typical main sequence star after binary evolution, which would produce a more subtle photometric signal at even earlier times which could have been missed by early-time observations.

In this study we place the strongest limits yet on the presence of $H\alpha$ emission in the nebular spectrum of a Type Ia supernova (SN Ia). We obtained a very high S/N spectrum of SN Ia 2011fe 274 days after maximum B -band light using the Multi-Object Double Spectrograph on the 8.4-meter Large Binocular Telescope. We generally followed the analysis procedures used by Leonard (2007), so our constraints should be directly comparable to earlier results. In Section 2 we describe our observations, in Section 3 we derive our $H\alpha$ limits, and we summarize our findings in Section 4.

2. Observations

We obtained five high-S/N spectra of SN 2011fe from 73 to 274 days after maximum B -band light using the first of the Multi-Object Double Spectrographs (MODS; Pogge et al. 2010) on the Large Binocular Telescope (LBT). The two channels of MODS allowed us to obtain wide spectral coverage (3200–10000Å) in a single exposure, which will make these observations useful for many future studies. Details of the observations and the flux standards used are listed in Table 1. All observations were taken through a 1'' wide slit. To perform basic CCD reductions on our spectra we followed the “MODS Basic CCD Reduction with modsCCDRed” manual². We then performed cosmic ray rejection using L.A.Cosmic (van Dokkum 2001) and combined each channel’s 2D spectra for each epoch. Next, we extracted the 1D sky-subtracted spectra

²modsCCDRed manual is available here <http://www.astronomy.ohio-state.edu/MODS/Manuals/MODSCCDRed.pdf>.

using the *apall* task in IRAF.³ Each spectrum was then wavelength and flux calibrated. We did not attempt to correct small-scale telluric absorption bands as performed by Leonard (2007). This will not adversely affect our results because the telluric absorptions occurs on wavelength scales smaller than the $H\alpha$ emission expected from the SN. This also avoids adding any noise from telluric spectra to our SN spectra.

Because our spectra were taken under non-photometric conditions with a relatively narrow ($1''$) slit, it is necessary to scale the fluxes of our spectra to place them on an absolute flux scale. To do this we performed aperture photometry on our Sloan r' (Fukugita et al. 1996) acquisition images using the IRAF package *apphot*. Because the SN was saturated in the acquisition image of the first epoch we must treat that spectrum separately. For the remaining epochs we used the four brightest stars in the image to put our photometry on the Sloan Digital Sky Survey (SDSS; York et al. 2000) Data Release 7 (Abazajian et al. 2009) magnitude system. Our r' -band magnitudes are reported in Table 1. We then scale the spectrum so that its synthetic r' -band photometry matches the computed r' -band aperture photometry. For the first epoch we scaled the spectrum such that a synthetic R -band magnitude (Bessell & Murphy 2012) matches the R -band magnitude for its epoch found by interpolating the combined R -band light curves of Richmond & Smith (2012) and Munari et al. (2012). To convert from the AB magnitude system (Oke 1974) of our synthetic photometry to the Vega magnitude system reported in Richmond & Smith (2012) and Munari et al. (2012), we use the conversion presented in Blanton & Roweis (2007). The factor by which each spectrum was multiplied is reported in Table 1. From the last four epochs' spectra, which are calibrated from the acquisition image but are also covered by the combined R -band light curves of Richmond & Smith (2012) and Munari et al. (2012), we estimate that our absolute flux calibration in the R -band (where $H\alpha$ is located) is accurate to 10% or better. In Figure 1 we show the $BVRI$ light curves of Richmond & Smith (2012) and Munari et al. (2012) as compared to our synthetic $BVRI$ photometry from the spectra for illustrative purposes. Figure 2 presents our calibrated spectra with obvious telluric features marked. Finally, we compare our nebular phase spectrum to the spectra presented in Leonard (2007), which provided the previous best limits on $H\alpha$.

³IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

Table 1. Observations

UT Date	Day	HJD −2,400,000	P.A. (deg)	Par. P.A. (deg)	Airmass	Flux standards	Seeing (arcsec)	Exposure (s)	r' (mag)	Scale factor
2011 Nov 23.52	73.02	55889.02	−78.0	−84.3 – −85.7	1.60 – 1.64	Feige110, G191-B2B	0.8 / 0.9	360.0 / 360.0	... ^a	1.07
2012 Jan 2.54	113.05	55929.05	−124.4	−134 – −139	1.11 – 1.12	Feige34	0.8 / 0.9	900.0 / 900.0	14.26 ± 0.03	1.93
2012 Mar 24.47	194.97	56010.97	−68.5	110 – 124	1.15 – 1.24	Feige67	0.5 / 0.7	2880.0 / 2160.0	16.35 ± 0.01	1.77
2012 Apr 27.27	228.77	56044.77	−2.0	−159 – 177	1.07 – 1.08	HZ44, BD+33d2642	0.9 / 1.1	3600.0 / 3600.1	17.06 ± 0.01	2.20
2012 Jun 12.16	274.66	56090.66	−32.7	−177 – 129	1.07 – 1.13	HZ44	0.7 / 0.7	7200.0 / 7200.0	17.95 ± 0.01	1.26

Note. — Observational and derived properties of our time series spectra of SN 2011fe. Days since maximum B brightness assume JD $t_{B\max} = 2455816.0 \pm 0.3$ (Richmond & Smith 2012). P.A. is the position angle of the spectrograph slit. Par. P.A. and airmass give the range of parallactic angles and airmasses at the start of each separate observation, respectively. Standard stars were observed on the same night as science observations and, when multiple standards were available, the computed response functions from each standard were averaged. Seeing gives the FWHM for the red / blue channels of the spatial profile in the combined 2d spectra. Exposure times are given for the red / blue channels separately. r' magnitude is derived from the acquisition images. Each flux calibrated spectra was multiplied by a scale factor derived in the R - or r' -band to place it on an absolute flux scale.

^aSN 2011fe was saturated in this epoch's acquisition images, so no reliable photometry was obtained.

As can be seen in Figure 2, our spectrum has a substantially higher S/N than the previous studies. These observations allow us to place even stronger limit on $H\alpha$ emission as we discuss in §3.

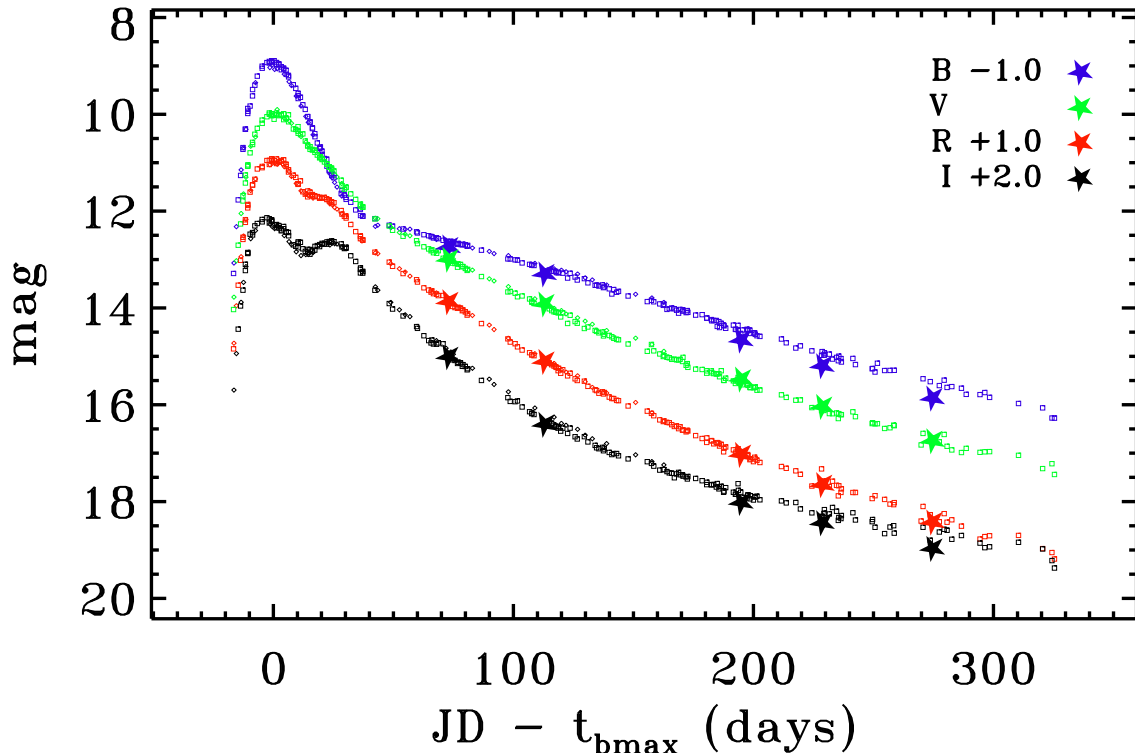


Fig. 1.— SN 2011fe light curves relative to the time of maximum B -band brightness ($t_{B\max} = 2455816.0 \pm 0.3$, Richmond & Smith 2012). Open diamonds and open squares show the $BVRI$ photometry from Richmond & Smith (2012) and Munari et al. (2012), respectively. Our synthetic $BVRI$ photometry are represented by filled stars. The first epoch is calibrated to an absolute flux scale using the Richmond & Smith (2012) R -band light curve so good agreement is expected. The rest of our spectra are calibrated using our r' -band acquisition images and SDSS DR7 photometry. From the second epoch we estimate that our absolute flux calibration is accurate to better than 10% in the R -band.

3. The Search for Hydrogen

In our search for $H\alpha$ emission in the spectrum of SN 2011fe, we closely follow the methods presented in Leonard (2007). We define a continuum by smoothing our spectra on scales large compared to expected $H\alpha$ feature, then subtract off this continuum and examine the residuals. We searched for $H\alpha$ emission within $\pm 1000 \text{ km s}^{-1}$ ($\pm 22 \text{ \AA}$) about $H\alpha$ at the redshift of M101, 0.000804 ± 0.000007 (de Vaucouleurs et al. 1991). We smoothed the spectrum with a second-order Savitsky-Golay smoothing polynomial (Press et al. 1992) with a width of 60 \AA . Our data requires this smaller smoothing scale than that employed by Leonard (2007)

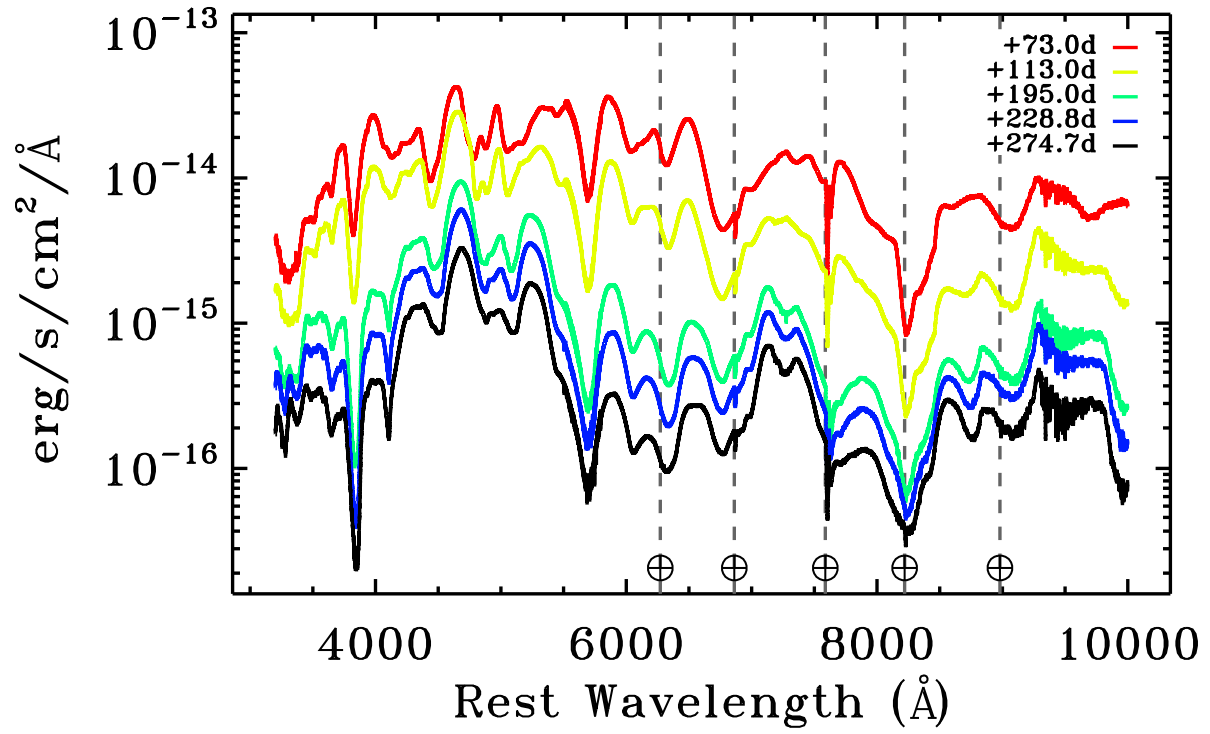


Fig. 2.— Rest-frame absolute-flux-calibrated spectra of SN 2011fe. Vertical dashed gray lines mark obvious telluric features. Spectra are labeled by days since maximum B brightness.

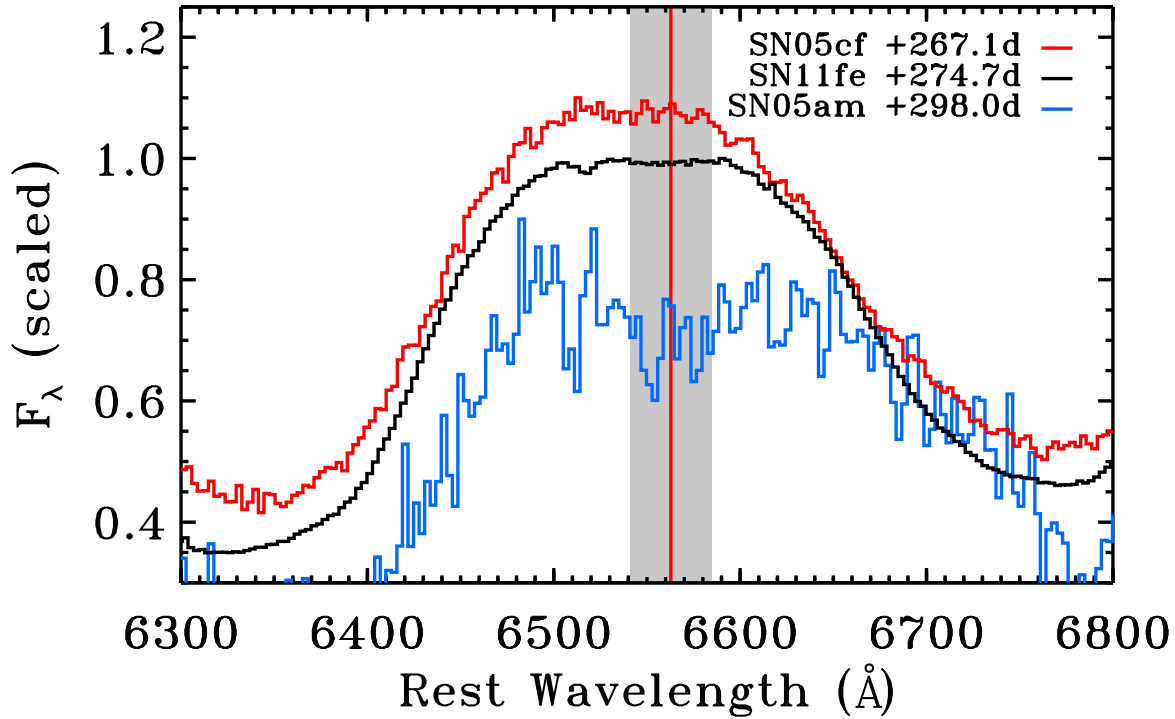


Fig. 3.— Comparison between our nebular phase spectrum of SN 2011fe and the spectra of SN 2005cf and SN 2005am presented in Leonard (2007) which previously provided the best limits on $H\alpha$ emission from the stripped material. Our spectra are binned to match the resolution of Leonard (2007). The rest wavelength of $H\alpha$ is indicated by the vertical red line and the shaded gray region shows where hydrogen emission would be expected ($\pm 1000 \text{ km s}^{-1} = \pm 22 \text{ \AA}$ about $H\alpha$). Our spectrum has a substantially higher S/N due to the proximity of SN 2011fe, allowing us to place a substantially stronger limit on $H\alpha$ emission in Section 3.

for a good continuum fit. It is, however, still significantly larger than the expected velocity width of any $H\alpha$ feature. Additionally, we smoothed over the telluric feature at 6510–6525 Å before smoothing the rest of the spectrum, because the feature was affecting the continuum determination near $H\alpha$.

Our nebular phase spectrum and continuum fit are shown in the top panel of Figure 4 in the vicinity of $H\alpha$ and are binned to their approximate spectral resolution.

We then subtracted the continuum from the binned spectrum and examined the residuals, shown in the bottom panel of Figure 4, for narrow $H\alpha$ emission. There is no evidence for any $H\alpha$ emission in the spectrum. The closest possible emission is the hump in the smoothed continuum at ~ 6575 – 6595 Å which is discussed in Section 3.2. More broadly, we found no narrow emission lines at any wavelength, including regions around $H\beta$, [O I] $\lambda\lambda 6300, 6364$, [O II] $\lambda\lambda 7319, 7330$, [O III] $\lambda\lambda 4959, 5007$, [Ca II] $\lambda\lambda 7291, 7324$, and [N II] $\lambda\lambda 6548, 6583$.

3.1. Statistical Limit

Following Leonard & Filippenko (2001) and Leonard (2007), we compute a 3σ upper bound on the equivalent width as

$$\begin{aligned} W_\lambda(3\sigma) &= 3\Delta\lambda \Delta I \sqrt{W_{\text{line}}/\Delta\lambda} \sqrt{1/B} \\ &= 3\Delta I \sqrt{W_{\text{line}} \Delta X}, \end{aligned} \quad (1)$$

where $\Delta\lambda$ is the width of a resolution element (in Å), ΔI is the 1σ root-mean-square fluctuation of the flux around a normalized continuum level, W_{line} is the full-width at half-maximum (FWHM) of the expected spectral feature (in Å), B is the number of bins per resolution element in the spectrum, and ΔX is the bin size of the spectrum (in Å). For the spectrum shown in in Figure 4, $\Delta I = 0.0024$ Å and $\Delta X = 4$ Å leading to $W_\lambda(3\sigma) = 0.067$ Å for $W_{\text{line}} = 22$ Å.

To translate this equivalent width constraint into a constraint on the amount of material stripped from a non-degenerate companion we follow the analysis of Mattila et al. (2005). Mattila et al. (2005) estimate that $0.5 M_\odot$ of solar-abundance material 380 days after explosion produces an $H\alpha$ feature with peak luminosity of $\sim 3.36 \times 10^{35}$ ergs s^{-1} Å $^{-1}$. Accounting for the distance to M101 and Galactic extinction towards M101 of $E(B-V) = 0.009$ mag (Schlegel et al. 1998) and assuming $R_V = 3.1$, the expected $H\alpha$ peak flux from $0.5 M_\odot$ of stripped material in SN 2011fe is 6.71×10^{-17} erg s^{-1} cm $^{-2}$ Å $^{-1}$. If we assume the line is Gaussian with FWHM 22 Å, then this feature would have an equivalent width of $W_\lambda(0.05 M_\odot) = 5.8$ Å. Scaling linearly from the equivalent width of the $H\alpha$ emission line to the amount of stripped material, we place an upper limit on the amount of solar-abundance material in SN 2011fe of $5.8 \times 10^{-4} M_\odot$.

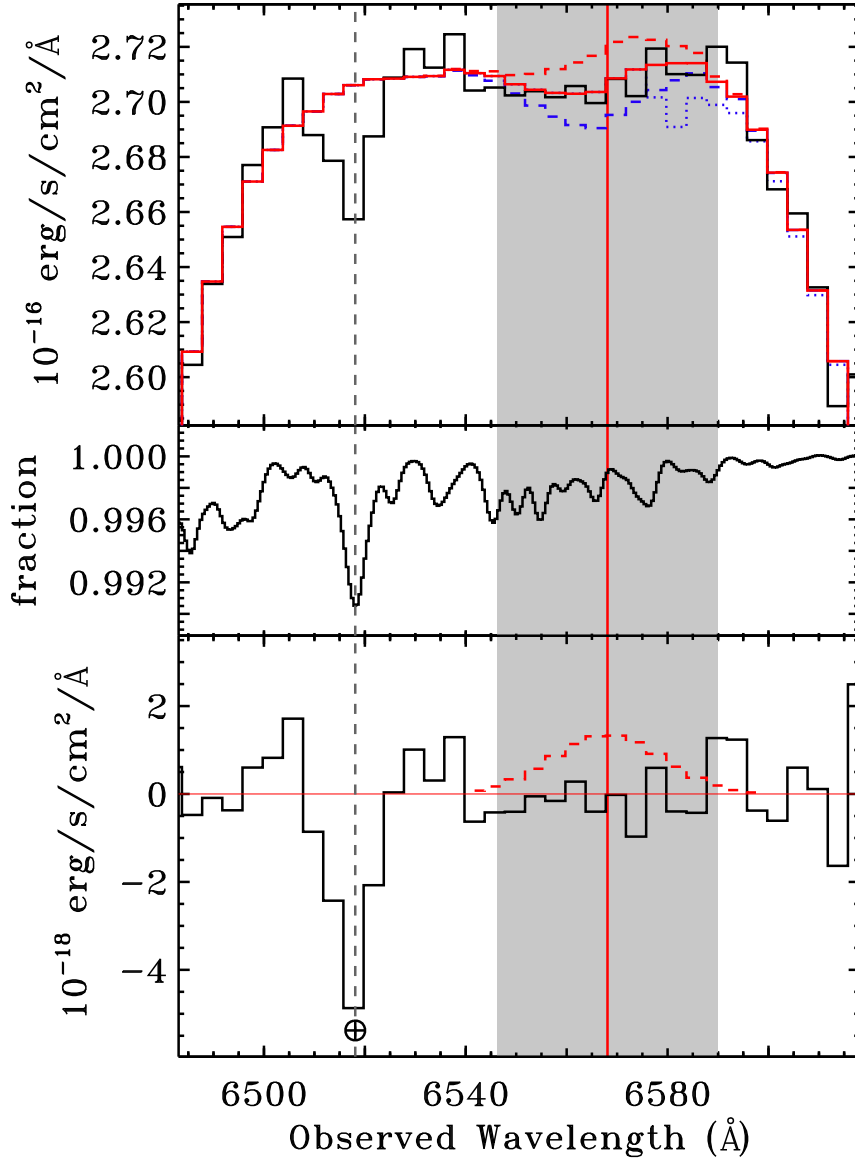


Fig. 4.— Nebular phase spectrum of SN 2011fe illustrating our conservative limit of $3.14 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ on the flux of $\text{H}\alpha$ emission. The rest wavelength of $\text{H}\alpha$ is indicated by the vertical red line and the shaded gray region shows where hydrogen emission would be expected ($\pm 1000 \text{ km s}^{-1} = \pm 22 \text{ \AA}$ about $\text{H}\alpha$). Adopting the models of Mattila et al. (2005), these limits translate into a $\lesssim 0.001 M_{\odot}$ limit on the amount of solar-abundance material stripped from the companion. Vertical dashed gray line marks a large telluric feature. *Top Panel:* SN spectrum binned to the approximate spectral resolution (4.0 \AA ; black solid); smoothed continuum (solid red); smoothed continuum with $\text{H}\alpha$ limit added (dashed red); smoothed continuum with $\text{H}\alpha$ limit subtracted to show what the underlying continuum would have to be to get the observed spectrum (dashed blue); and smoothed continuum with $\text{H}\alpha$ limit subtracted, assuming the velocity distribution discussed in Section 3.2 (dotted blue). *Middle Panel:* The location of telluric water vapor absorption lines illustrated by the ESO SM-01 Sky Model Mode Version 1.3.1. *Bottom Panel:* SN spectrum with smoothed continuum subtracted (solid black) as compared to the $\text{H}\alpha$ limit (dashed red). Horizontal solid red line marks zero.

3.2. Conservative Limit

Unlike the Leonard (2007) study, the main uncertainty in our $H\alpha$ limit arises from the continuum determination and the $H\alpha$ line profile rather than the photon noise of our spectrum. For example there is a small amplitude feature in the observed spectra at $6575\text{--}6595\text{ \AA}$. To test if this spectral feature could be attributed to material asymmetrically stripped from a companion we took the velocity distribution of stripped material from Figure 9 of Liu et al. (2012) and assumed it was narrowly distributed along a line (see Figure 11 of Liu et al. 2012). We found that a total flux of $2.20 \times 10^{-17}\text{ erg s}^{-1}\text{ cm}^{-2}$ and an angle between the stripped material and our line of sight of 30.0° best reproduces the feature in our smoothed continuum. To be conservative, we take a less stringent limit on the total $H\alpha$ flux of $3.14 \times 10^{-17}\text{ erg s}^{-1}\text{ cm}^{-2}$, which is weaker than our statistical limit and too large to explain the spectral feature between $6575\text{--}6595\text{ \AA}$ shown in Figure 4. This limit corresponds to an equivalent width of 0.12 \AA , a total $H\alpha$ luminosity of $1.57 \times 10^{35}\text{ erg s}^{-1}$, and 0.001 M_\odot of solar-abundance material adopting the models of Mattila et al. (2005). We emphasize that whether this feature is $H\alpha$ emission or clumpiness in the underlying SN continuum, our conservative flux limit holds.

4. Summary

We obtained five deep, medium resolution, spectra of the nearby “plain vanilla” SN Ia 2011fe with LBT/MODS from 73–274 days after maximum B -band light. With the last nebular phase spectrum we place the deepest flux limits on narrow $H\alpha$ emission yet for a SN Ia. Determining the late-time $H\alpha$ emission in SNe Ia spectra requires difficult radiative transfer calculations, but adopting the models of Mattila et al. (2005), our limit translates into an upper limit on the mass of solar-abundance material of $\lesssim 0.001\text{ M}_\odot$, an order of a magnitude smaller than previous limits (Leonard 2007). However, two important theoretical questions from Mattila et al. (2005) need to be confirmed by additional modeling. First, the opacity of the high-velocity iron-rich ejecta should be recomputed to confirm when the SN ejecta becomes optically thin. Second, the expected excitation for $H\alpha$ emission by gamma-rays should be modeled in detail. These issues notwithstanding, our limit based on the Mattila et al. (2005) models poses a significant challenge to SD models, including more exotic variations proposed to evade the previous constraints.

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the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is <http://www.sdss.org/>. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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